Hybrid Wet/Dry Cooling for Power Plants

Parabolic Trough Technology Workshop
February 14, 2006

Chuck Kutscher

Aaron Buys

Chris Gladden

NREL

Outline

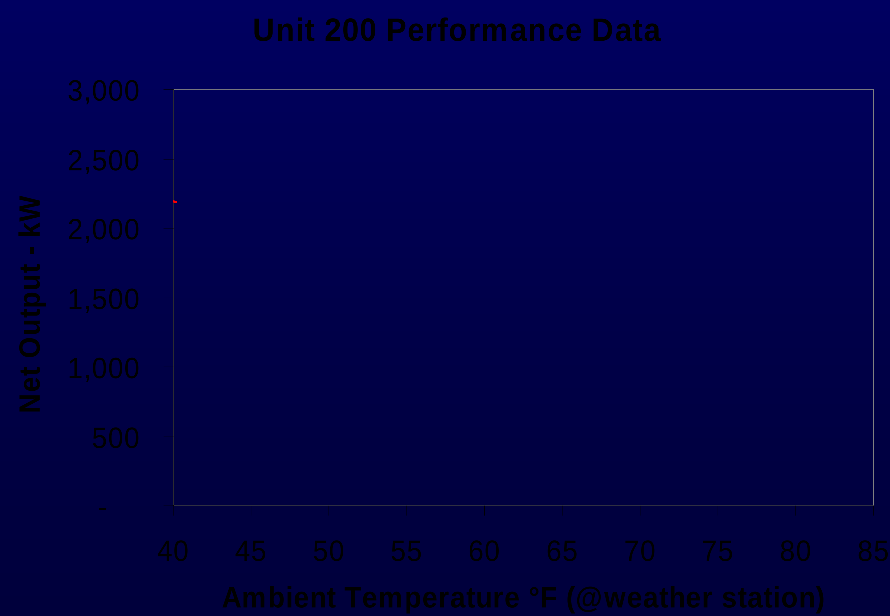
- Overview of cooling options
- Analysis of evaporative enhancement of air-cooled geothermal power plants
- Field measurements at geothermal plant
- Preliminary analysis of trough plant
- Improvements to air-cooled condensers

Water-Saving Options

Approach	**Pros**	**Cons**
ACC + WCC in Series	- ACC can handle desuperheating load	- Cost of dual equipment - Condensate temp. very limited
ACC + WCC in Parallel	- Simple design - Improves approach to dry bulb	- Condensate temp. limited by dry bulb
ACC w/ Evap Media	- Can achieve good approach to wet bulb on inlet air	- Cost of media - Pressure drop lowers flow rate and LMTD
ACC w/ Spray Nozzles	- Simple, low cost of nozzles - Low pressure drop	- Overspray and water waste - Cost of water treatment or mist eliminator - Nozzle maintenance - Potential damage to finned tubes
Deluge of ACC	- Highest enhancement	- Water treatment or protective coating needed

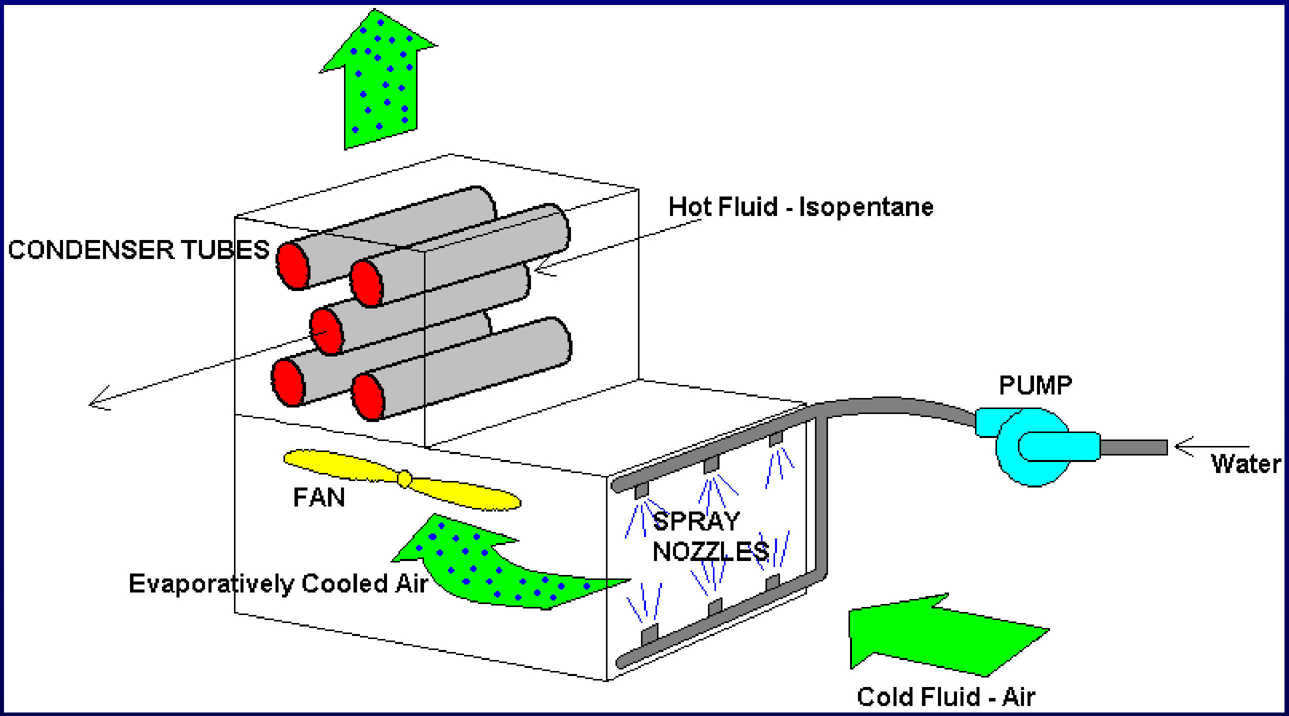
Relevance

- Air-cooled geothermal plants especially susceptible to high ambient temperature
- Plant power decreases ~1% of rated power for every 1ºF rise in condenser temperature
- Output of air-cooled plant can drop > 50% in summer, when electricity is highly valued



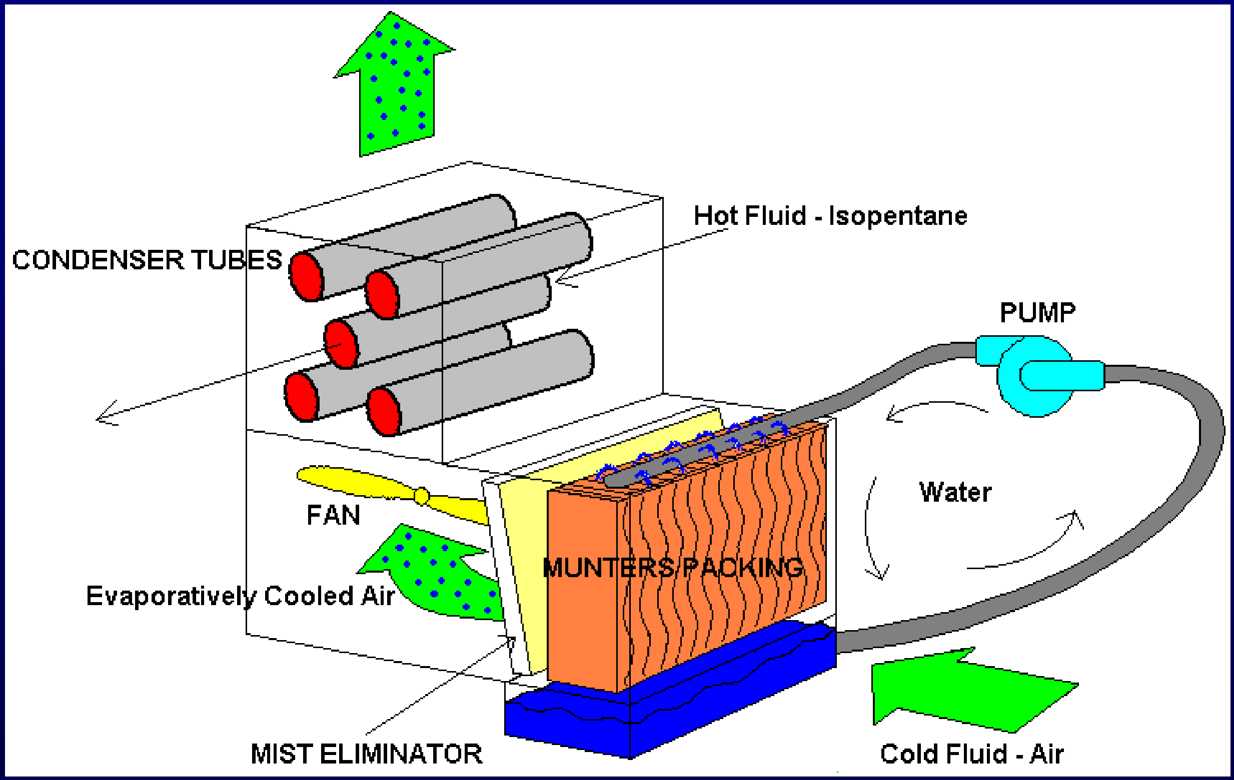
Spreadsheet Model of Evaporative Enhancements to Existing Air-Cooled Plants

System 1 - Spray Cooling



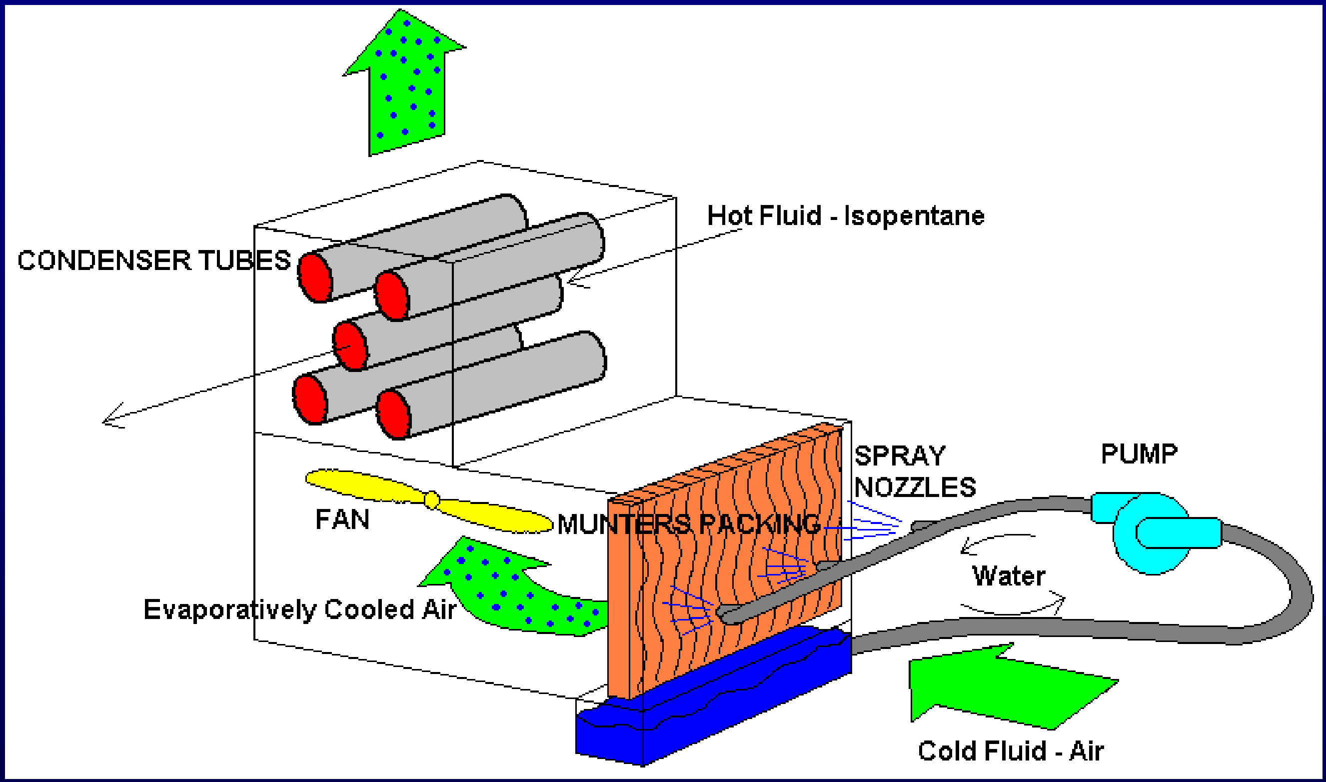
- Low cost, low air pressure drop
- High water pressure
- Over-spray and carryover or cost of mist eliminator
- Nozzle clogging

System 2 - Munters Cooling



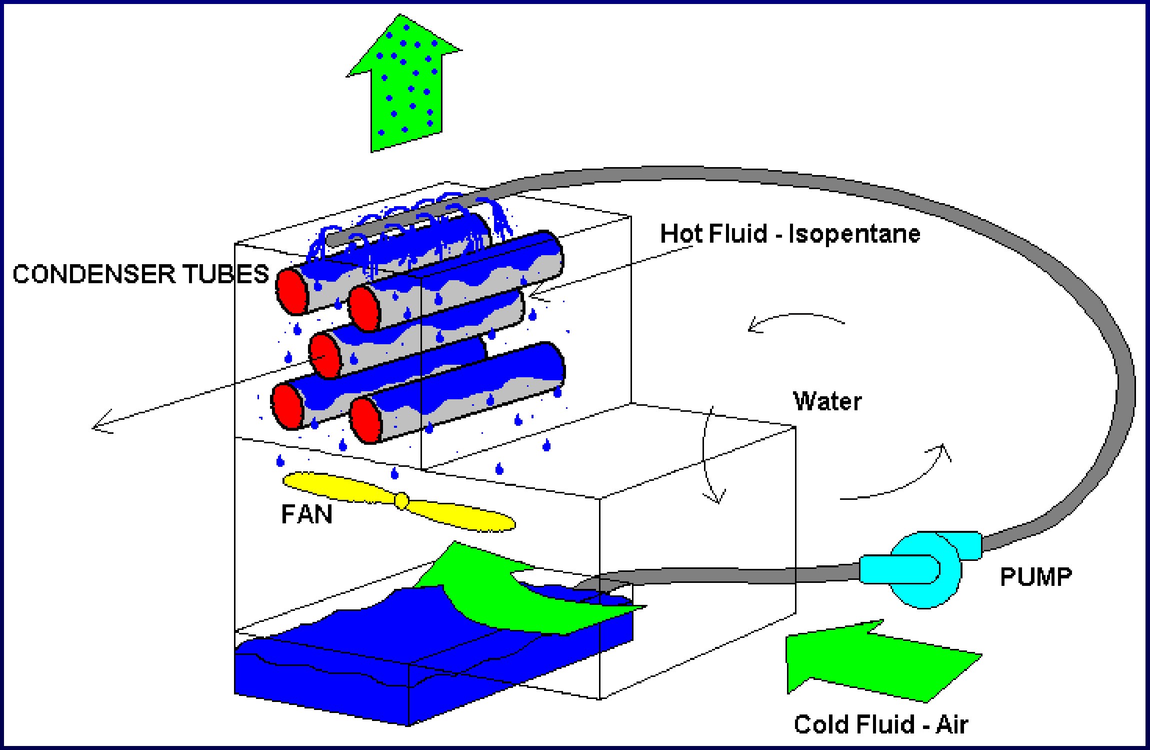
- High efficiency, minimum carryover
- High air pressure drop (reduces air flow rate and decreases LMTD)
- High cost

System 3 – Hybrid Cooling

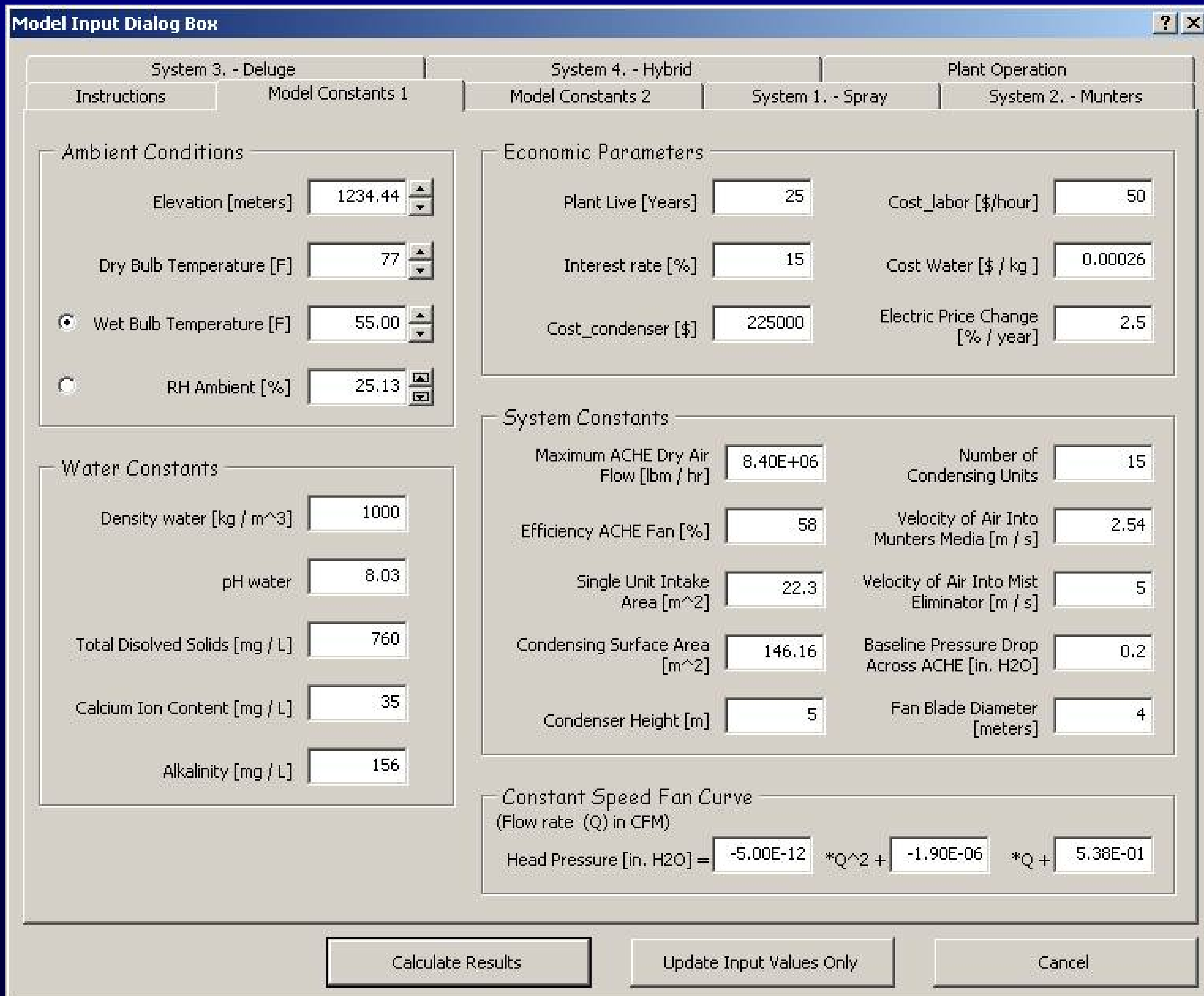


- Inexpensive and simple, used in poultry industry
- Over-spray, carryover, and nozzle cleaning

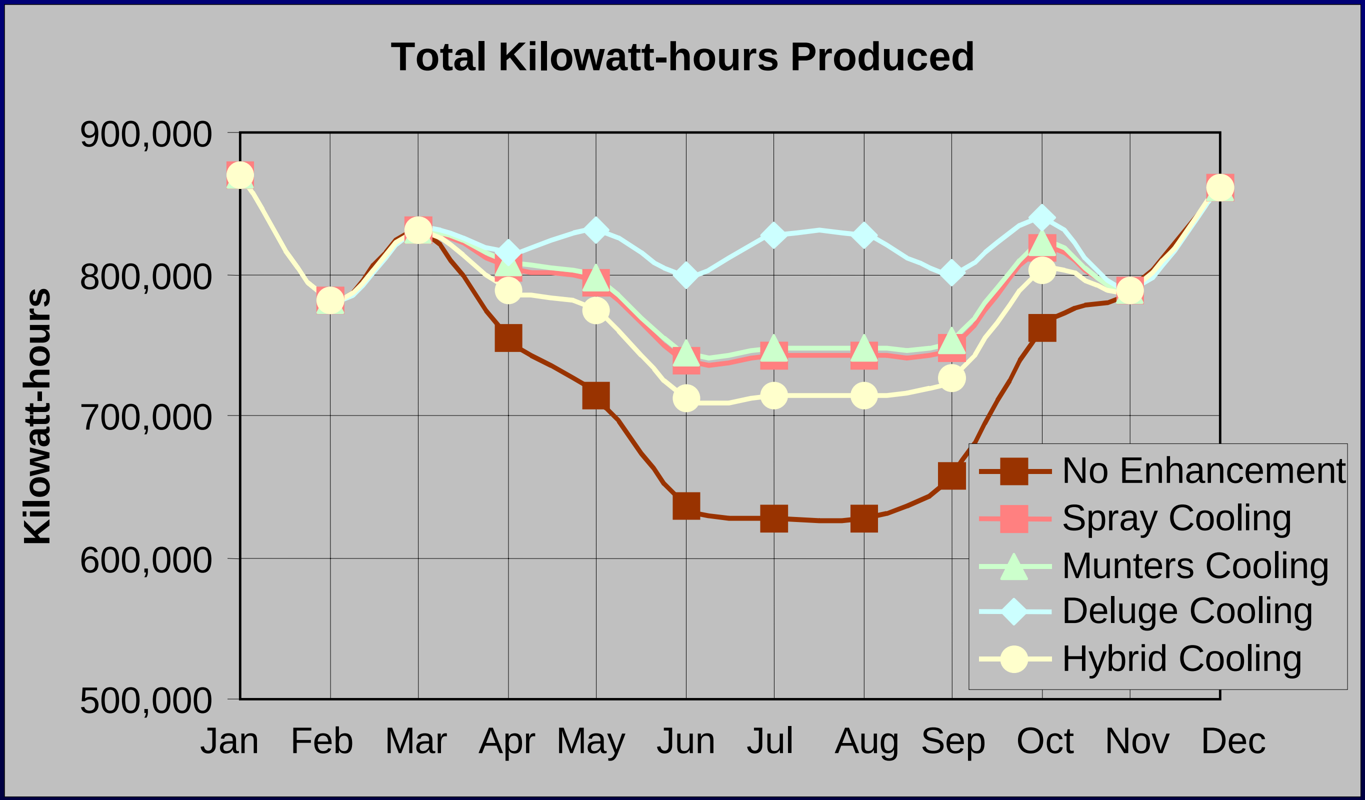
System 4 – Deluge Cooling



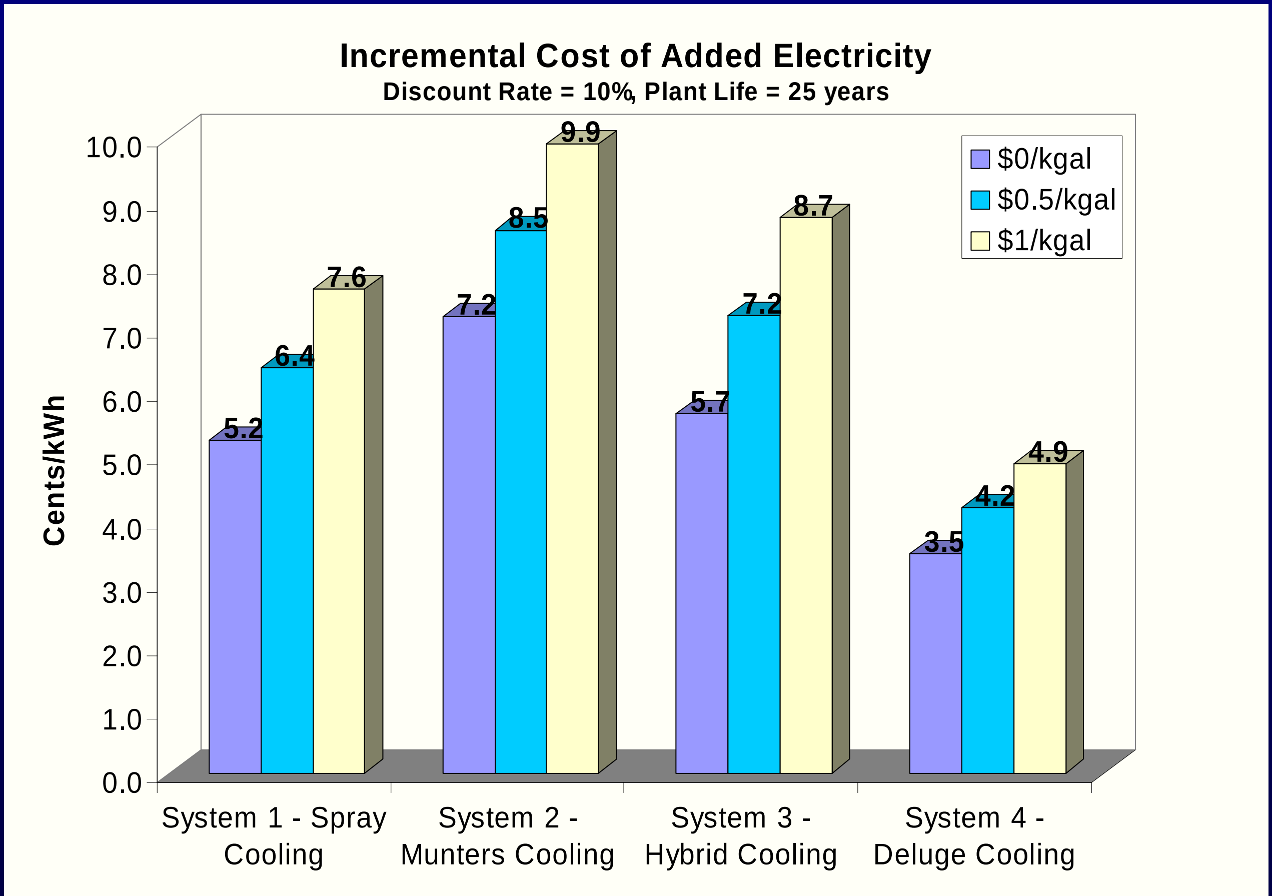
- Excellent performance
- Danger of scaling and deposition without pure water


Model Input Dialog Box
System 3. - Deluge
System 4. - Hybrid
Plant Operation
Instructions
Model Constants 1
Model Constants 2
System 1. - Spray
System 2. - Munters
Ambient Conditions
Elevation [meters] 1234.44
Dry Bulb Temperature [F] 77
Wet Bulb Temperature [F] 55.00
RH Ambient [%] 25.13
Water Constants
Density water [kg / m^3] 1000
pH water 8.03
Total Disolved Solids [mg / L] 760
Calcium Ion Content [mg / L] 35
Alkalinity [mg / L] 156
Economic Parameters
Plant Live [Years] 25
Cost_labor [$/hour] 50
Interest rate [%] 15
Cost Water [$ / kg] 0.00026
Cost_condenser [$] 225000
Electric Price Change [% / year] 2.5
System Constants
Maximum ACHE Dry Air Flow [lbm / hr] 8.40E+06
Number of Condensing Units 15
Efficiency ACHE Fan [%] 58
Velocity of Air Into Munters Media [m / s] 2.54
Single Unit Intake Area [m^2] 22.3
Velocity of Air Into Mist Eliminator [m / s] 5
Condensing Surface Area [m^2] 146.16
Baseline Pressure Drop Across ACHE [in. H2O] 0.2
Condenser Height [m] 5
Fan Blade Diameter [meters] 4
Constant Speed Fan Curve
(Flow rate (Q) in CFM)
Head Pressure [in. H2O] = -5.00E-12 *Q^2 + -1.90E-06 *Q + 5.38E-01
Calculate Results
Update Input Values Only
Cancel

Example Analysis: Net Power Produced



Example Cost Results



Note: Value of electricity will be affected by time-of-day rates and capacity payments.

Geothermal Analysis Conclusions

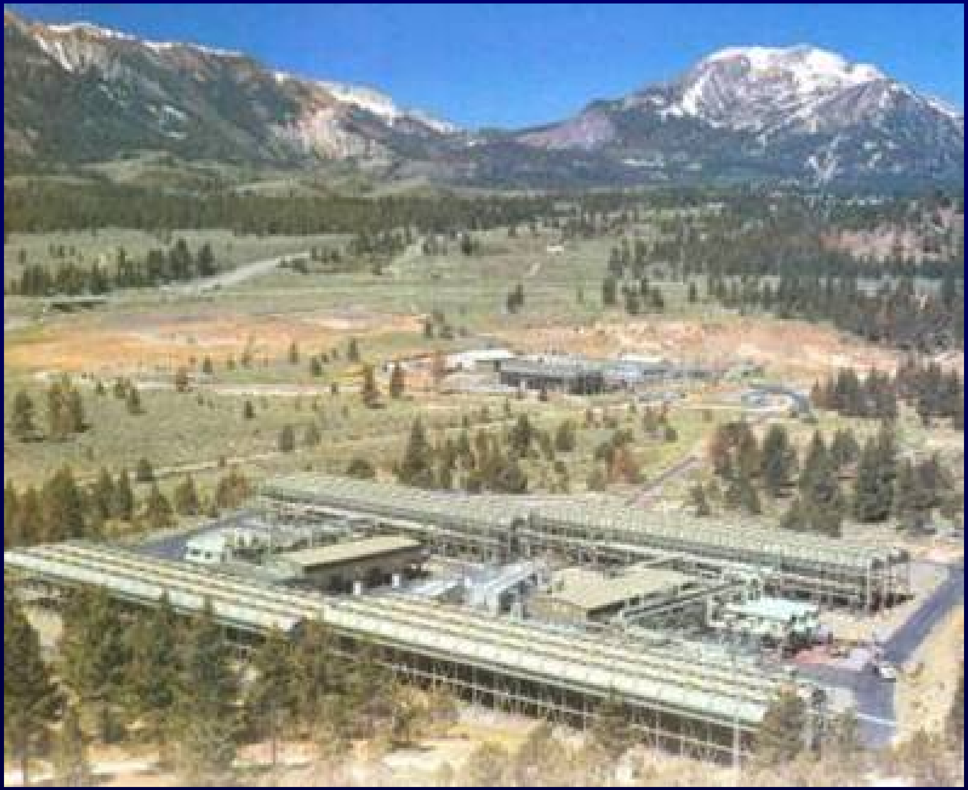
- Deluge most attractive if scaling/corrosion issues can be addressed
- Systems 1 to 3 obtain ~40 kWh/kgal of water; deluge can produce an average of ~60 kWh/kgal
- Results very sensitive to water costs, electric rate structure, installation costs

Coated Fin Test Results

OMP-coated fin unaffected by salt spray

Plain fin pitted

Measurements at Mammoth



Measurements at Mammoth Binary-Cycle Geothermal Power Plant

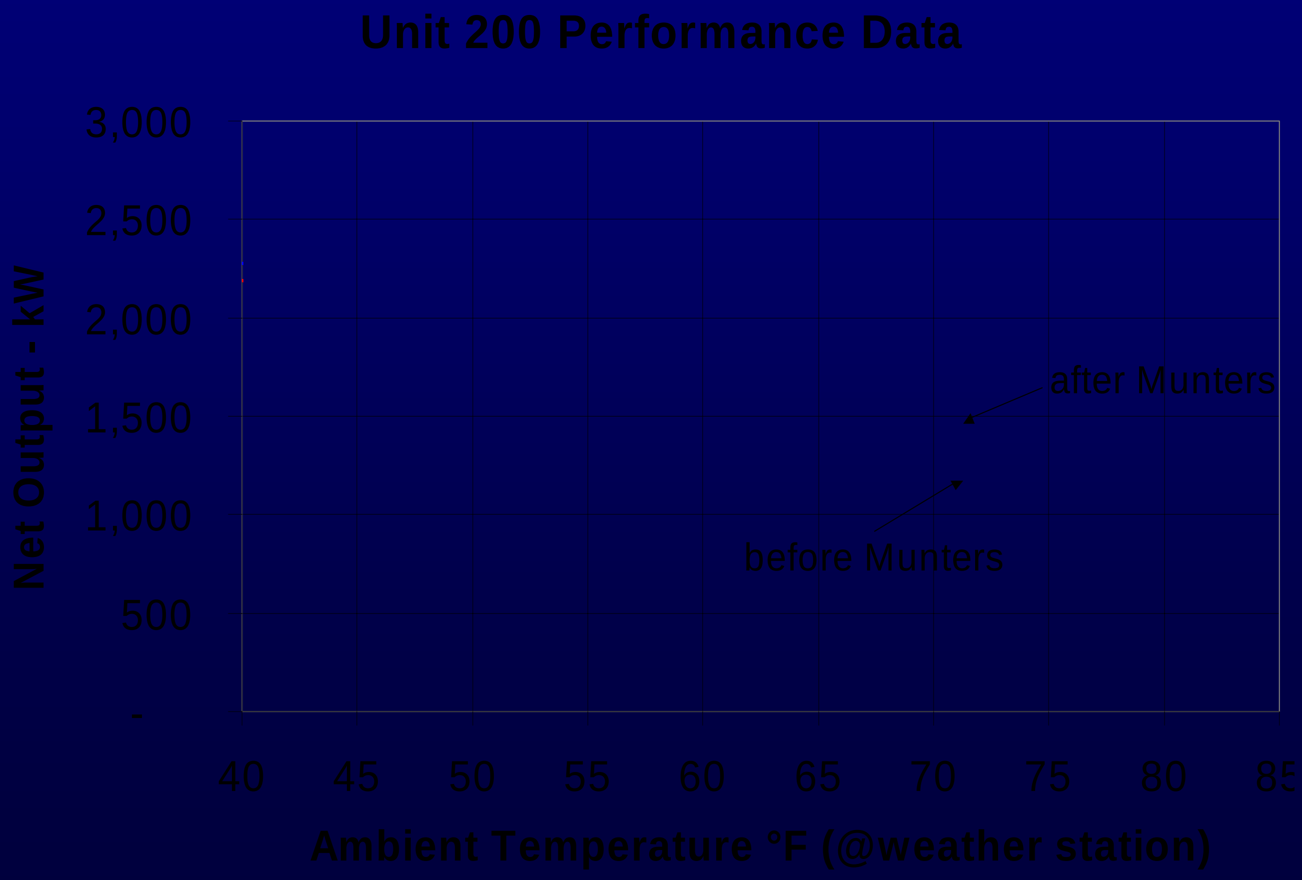
Munters system

Hybrid spray/Munters system

Mammoth Measurement Results: 2001

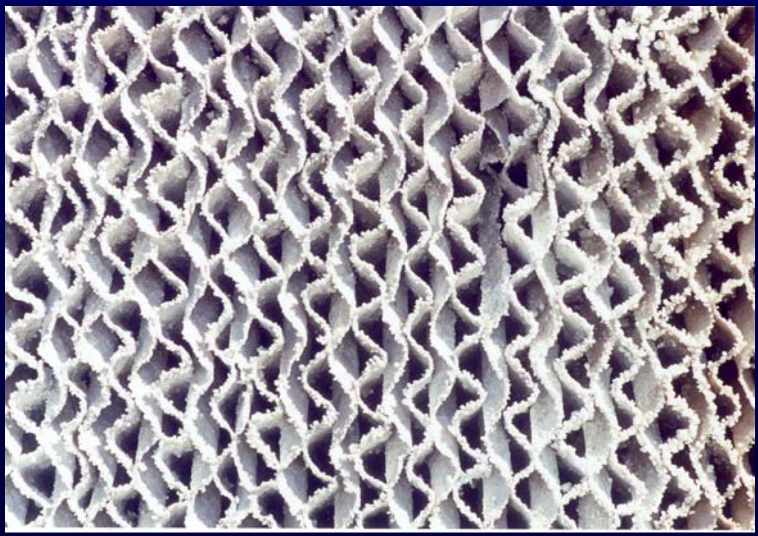
- Field instrumentation: Type T thermocouples, optical dew point (chilled mirror) hygrometer, handheld anemometer
- Munters had 79% saturation efficiency; hybrid was 50%
- Flow rate with Munters dropped 22-28%
- Munters increased net power 62% (800 kW to 1,300 kW) at 78ºF ambient

Munters Performance at Mammoth



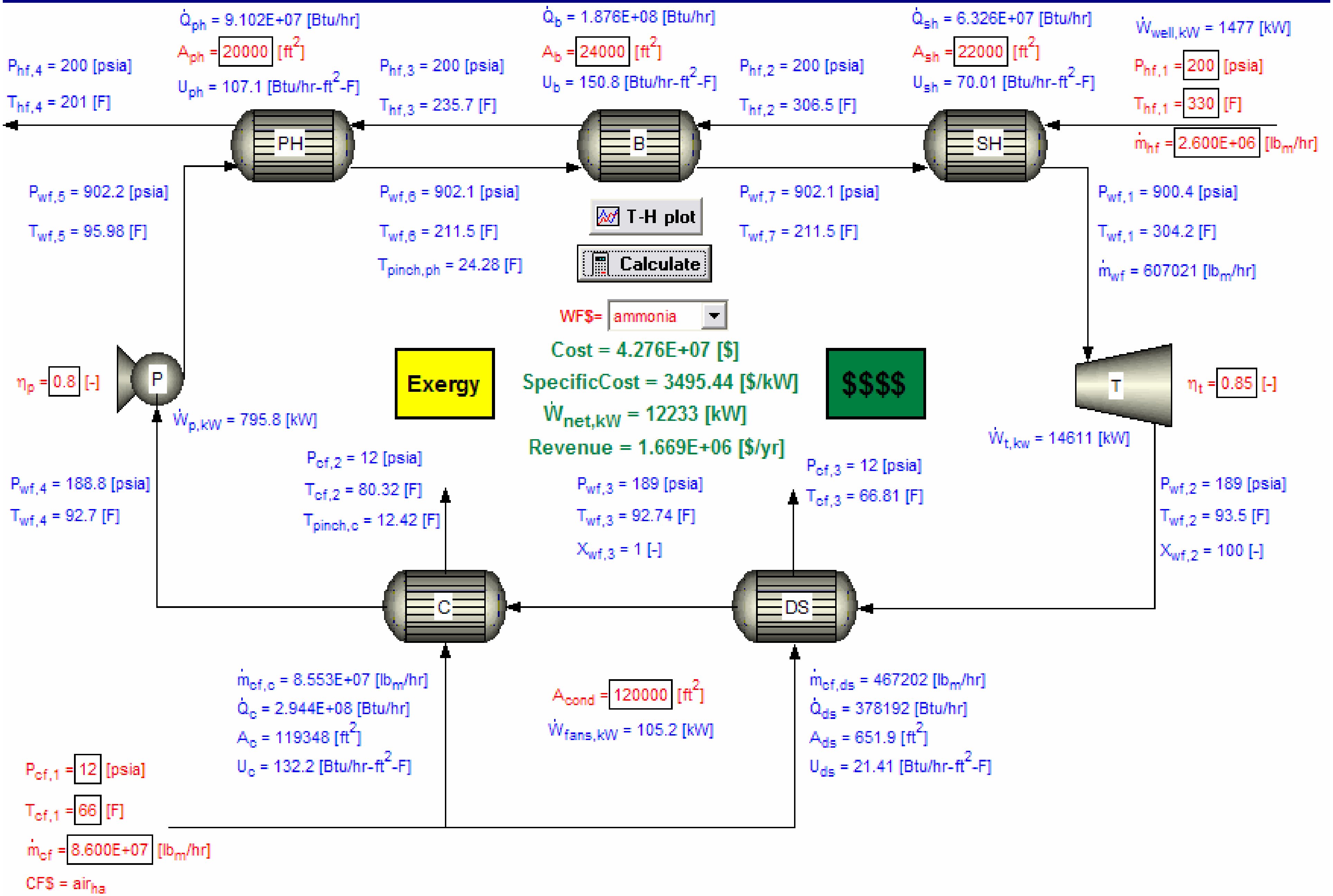
Mammoth Measurement Results: 2002

- Munters system modified, brine used for cooling water. Munters efficiency dropped from 79% to 66%

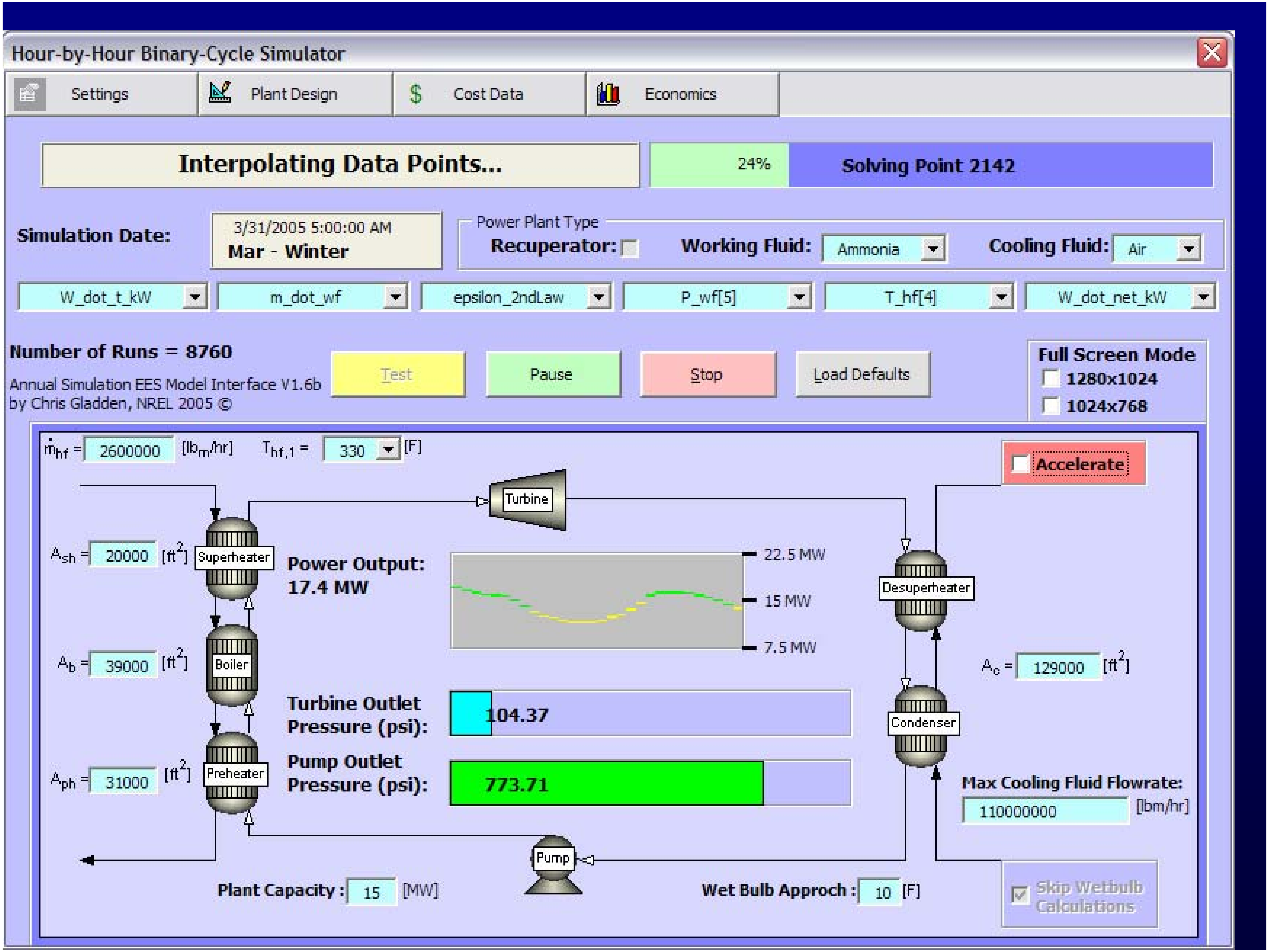


Geothermal Conclusions

- All operators of air-cooled plants interested in evaporative enhancement
- Costs at existing plants are site-specific and negotiable; $0.50 to $2.00 per thousand gallons
- Reclaimed water becoming more widely available
- Two-Phase Engineering showed successful use of nozzles with brine
- Can reduce average cost of electricity by about 0.3 ¢/kWh, depending on cost of water
- Capacity payments can be as high as 30 ¢/kWh and lower average cost of electricity by 2–3 ¢/kWh

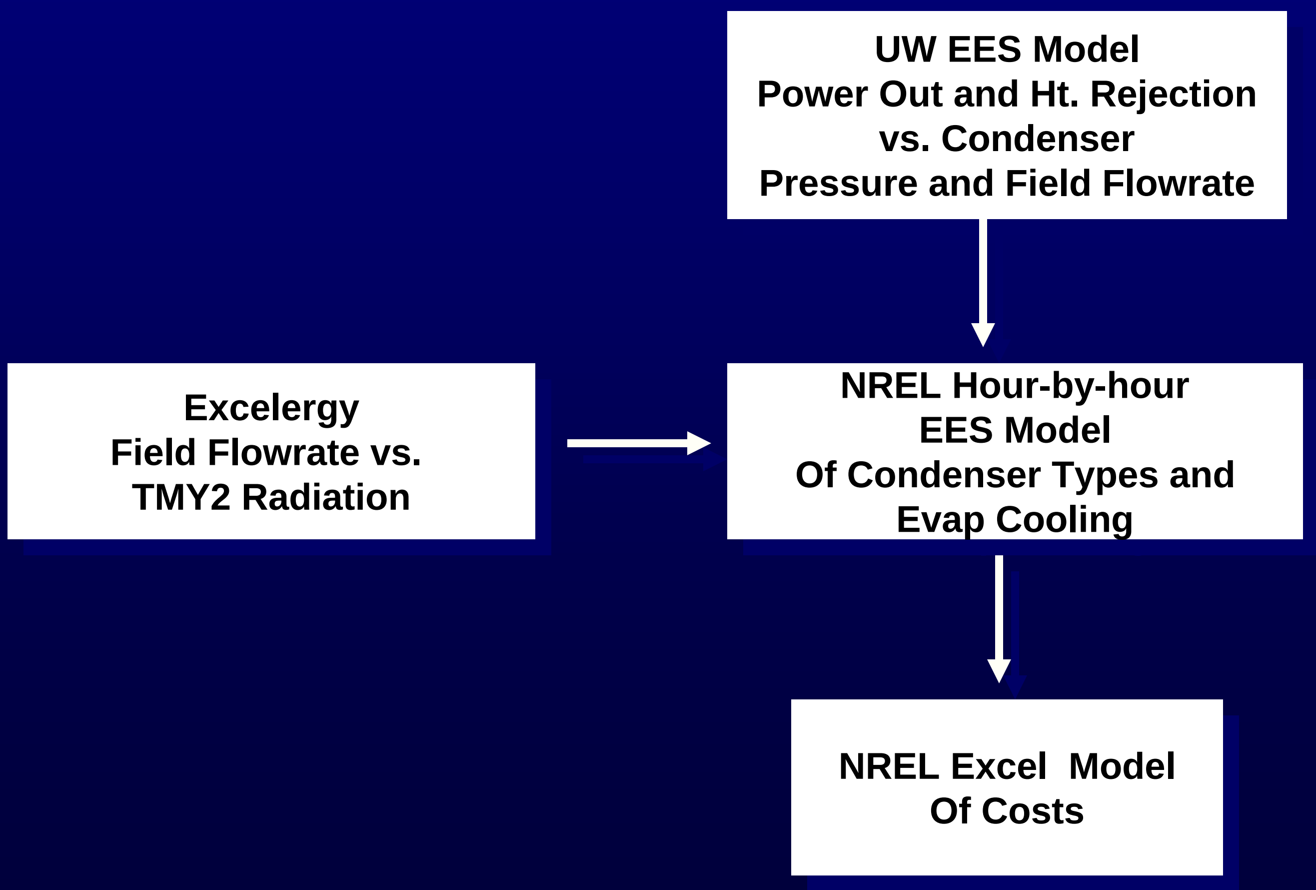


$\dot{Q}_{ph}$ = 9.102E+07 [Btu/hr]
A_{ph} = 20000 [ft^2]
U_{ph} = 107.1 [Btu/hr-ft^2-F]
$\dot{Q}_b$ = 1.876E+08 [Btu/hr]
A_b = 24000 [ft^2]
U_b = 150.8 [Btu/hr-ft^2-F]
$\dot{Q}_{sh}$ = 6.326E+07 [Btu/hr]
A_{sh} = 22000 [ft^2]
U_{sh} = 70.01 [Btu/hr-ft^2-F]
$\dot{W}_{well,kW}$ = 1477 [kW]
$P_{hf,1}$ = 200 [psia]
$T_{hf,1}$ = 330 [F]
$\dot{m}_{hf}$ = 2.600E+06 [lb$_m$/hr]
$P_{hf,4}$ = 200 [psia]
$T_{hf,4}$ = 201 [F]
$P_{hf,3}$ = 200 [psia]
$T_{hf,3}$ = 235.7 [F]
$P_{hf,2}$ = 200 [psia]
$T_{hf,2}$ = 306.5 [F]
PH
B
SH
$P_{wf,5}$ = 902.2 [psia]
$T_{wf,5}$ = 95.98 [F]
$P_{wf,6}$ = 902.1 [psia]
$T_{wf,6}$ = 211.5 [F]
$T_{pinch,ph}$ = 24.28 [F]
T-H plot
Calculate
$P_{wf,7}$ = 902.1 [psia]
$T_{wf,7}$ = 211.5 [F]
$P_{wf,1}$ = 900.4 [psia]
$T_{wf,1}$ = 304.2 [F]
$\dot{m}_{wf}$ = 607021 [lb$_m$/hr]
WF$= ammonia
Cost = 4.276E+07 [$]
SpecificCost = 3495.44 [$/kW]
$\dot{W}_{net,kW}$ = 12233 [kW]
Revenue = 1.669E+06 [$/yr]
Exergy
$$$$
η_p = 0.8 [-]
P
$\dot{W}_{p,kW}$ = 795.8 [kW]
T
η_t = 0.85 [-]
$\dot{W}_{t,kw}$ = 14611 [kW]
$P_{wf,4}$ = 188.8 [psia]
$T_{wf,4}$ = 92.7 [F]
$P_{cf,2}$ = 12 [psia]
$T_{cf,2}$ = 80.32 [F]
$T_{pinch,c}$ = 12.42 [F]
$P_{wf,3}$ = 189 [psia]
$T_{wf,3}$ = 92.74 [F]
$X_{wf,3}$ = 1 [-]
$P_{cf,3}$ = 12 [psia]
$T_{cf,3}$ = 66.81 [F]
$P_{wf,2}$ = 189 [psia]
$T_{wf,2}$ = 93.5 [F]
$X_{wf,2}$ = 100 [-]
C
DS
$\dot{m}_{cf,c}$ = 8.553E+07 [lb$_m$/hr]
$\dot{Q}_c$ = 2.944E+08 [Btu/hr]
A_c = 119348 [ft^2]
U_c = 132.2 [Btu/hr-ft^2-F]
A_{cond} = 120000 [ft^2]
$\dot{W}_{fans,kW}$ = 105.2 [kW]
$\dot{m}_{cf,ds}$ = 467202 [lb$_m$/hr]
$\dot{Q}_{ds}$ = 378192 [Btu/hr]
A_{ds} = 651.9 [ft^2]
U_{ds} = 21.41 [Btu/hr-ft^2-F]
$P_{cf,1}$ = 12 [psia]
$T_{cf,1}$ = 66 [F]
$\dot{m}_{cf}$ = 8.600E+07 [lb$_m$/hr]
CF$ = air$_{ha}$



Hour-by-Hour Binary-Cycle Simulator
Settings
Plant Design
Cost Data
Economics
Interpolating Data Points...
24%
Solving Point 2142
Simulation Date:
3/31/2005 5:00:00 AM
Mar - Winter
Power Plant Type
Recuperator:
Working Fluid:
Ammonia
Cooling Fluid:
Air
W_dot_t_kW
m_dot_wf
epsilon_2ndLaw
P_wf[5]
T_hf[4]
W_dot_net_kW
Number of Runs = 8760
Annual Simulation EES Model Interface V1.6b
by Chris Gladden, NREL 2005 ©
Test
Pause
Stop
Load Defaults
Full Screen Mode
1280x1024
1024x768
$\dot{m}_{hf}$ = 2600000 [lbm/hr]
$T_{hf,1}$ = 330 [F]
Accelerate
Turbine
A_{sh} = 20000 [ft²]
Superheater
Power Output:
17.4 MW
22.5 MW
15 MW
7.5 MW
Desuperheater
A_b = 39000 [ft²]
Boiler
A_c = 129000 [ft²]
Turbine Outlet Pressure (psi):
104.37
Condenser
A_{ph} = 31000 [ft²]
Preheater
Pump Outlet Pressure (psi):
773.71
Max Cooling Fluid Flowrate:
110000000 [lbm/hr]
Pump
Plant Capacity : 15 [MW]
Wet Bulb Approch : 10 [F]
Skip Wetbulb Calculations

Parabolic Trough Plant Preliminary Analysis



Cases Examined

- Air-Cooled
- Water-Cooled
- Air-Cooled with Spray Enhancement

General Assumptions

- 30 MW_e SEGS plant, Daggett weather
- \$0.18/kWh electricity (€0.15/kWh)
- Water at \$1.95/kgal (\$515/m^3, €430/m^3)
- 15% interest rate
- 30-year life

Water-Cooled Plant

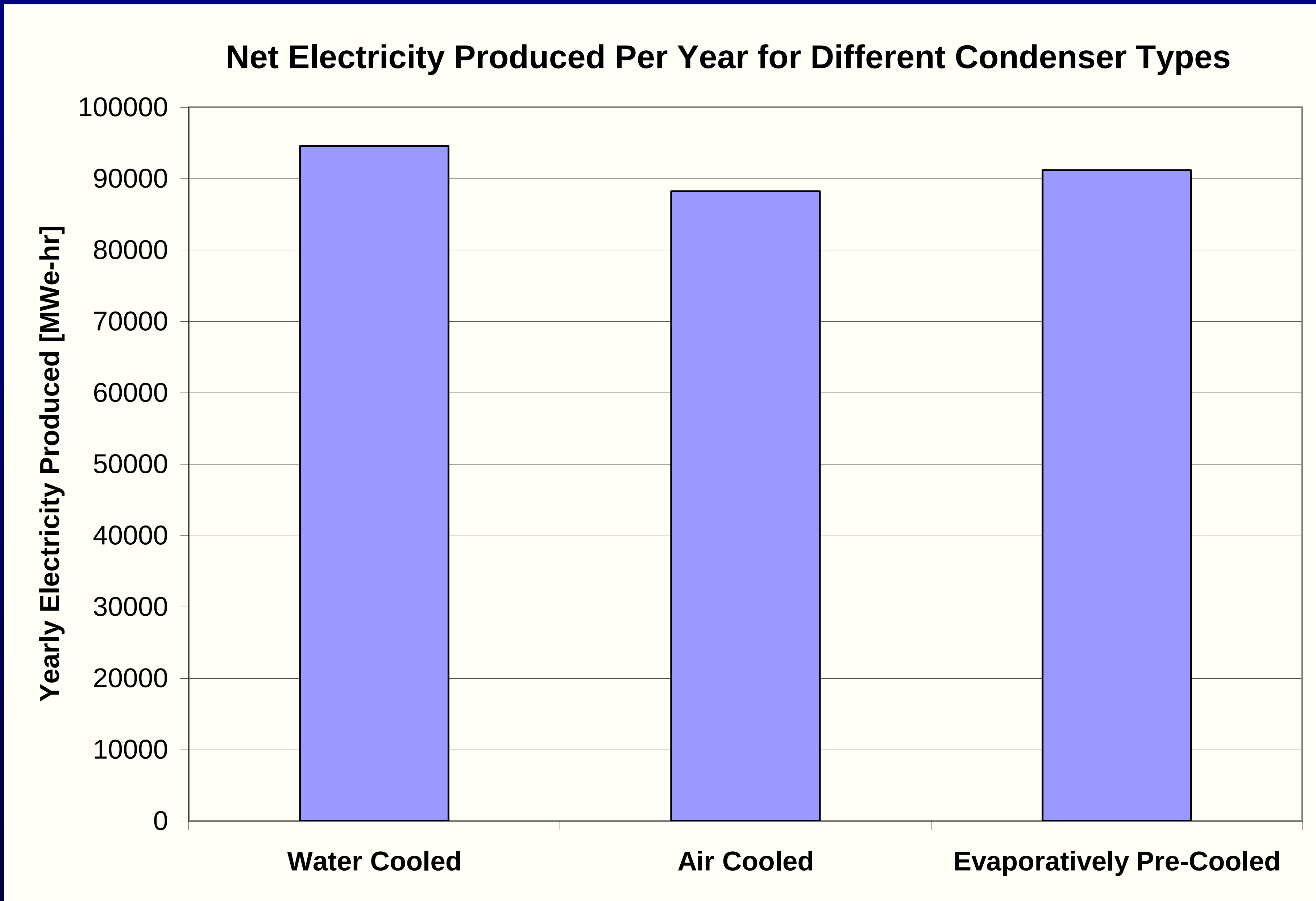
- Shell-and-tube condenser + cooling tower
- T_{wb} = 68°F (20°C)
- Approach = 10°F (5.6°C)
- Range = 20°F (11.1°C)
- Pinch = 5°F (2.8°C)
- U = 400 Btu/h-ft^2-°F (2270 W/m^2-°C)

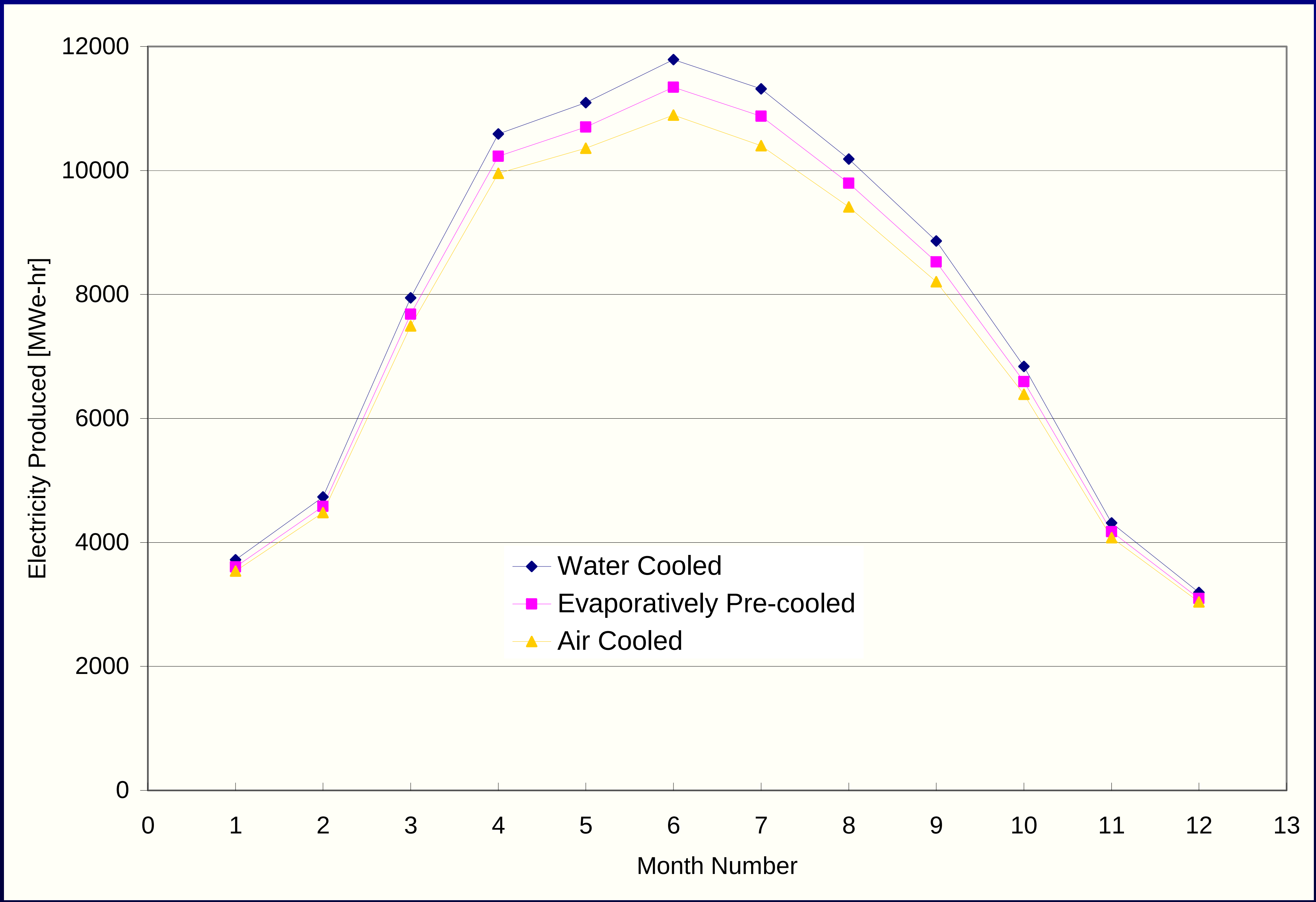
Air-Cooled Plant

- Finned tube condenser
- Tdb = 104°F (40°C)
- ITD = 40°F (22°C)
- Pinch = 5°F (2.8°C)
- U = 150 Btu/h-ft^2-°F (850 W/m^2-°C)

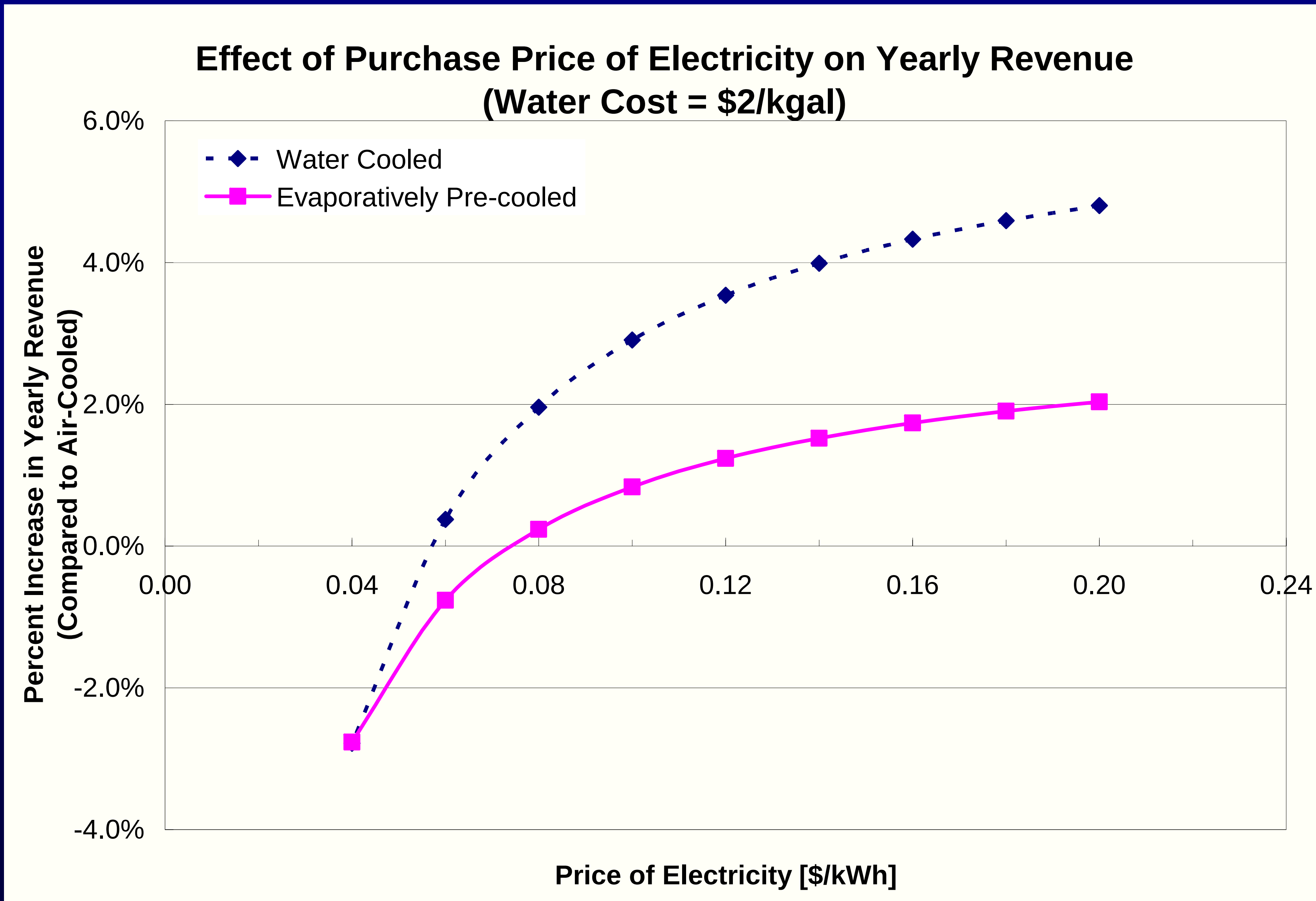
Evaporative Pre-Cooling

- 300 psig spray nozzles
- 70% evaporation efficiency
- 80% saturation efficiency
- Munters DRIFdek mist eliminator

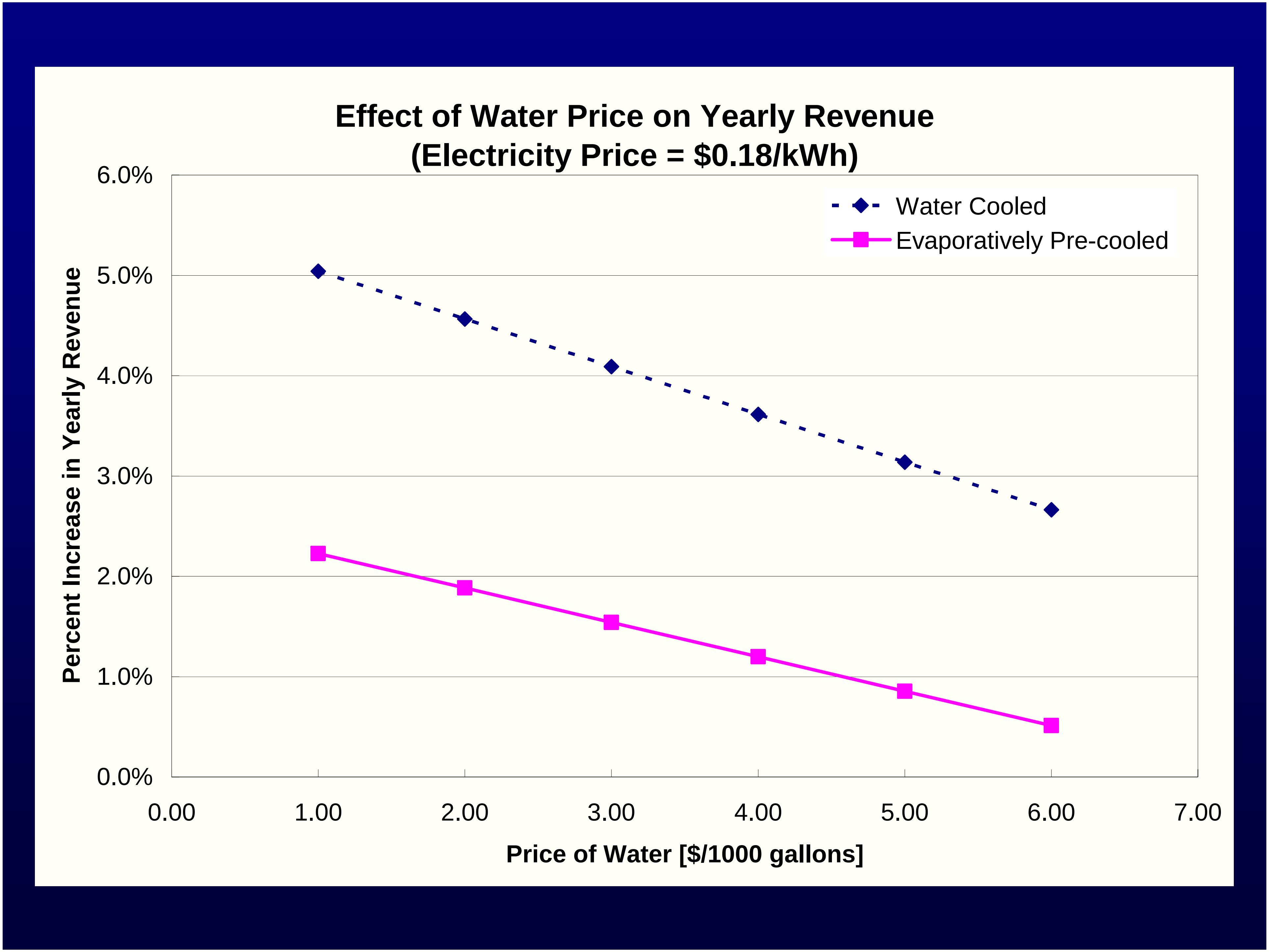

Net Electricity Produced Per Year for Different Condenser Types
Yearly Electricity Produced [MWe-hr]
100000
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
Water Cooled
Air Cooled
Evaporatively Pre-Cooled



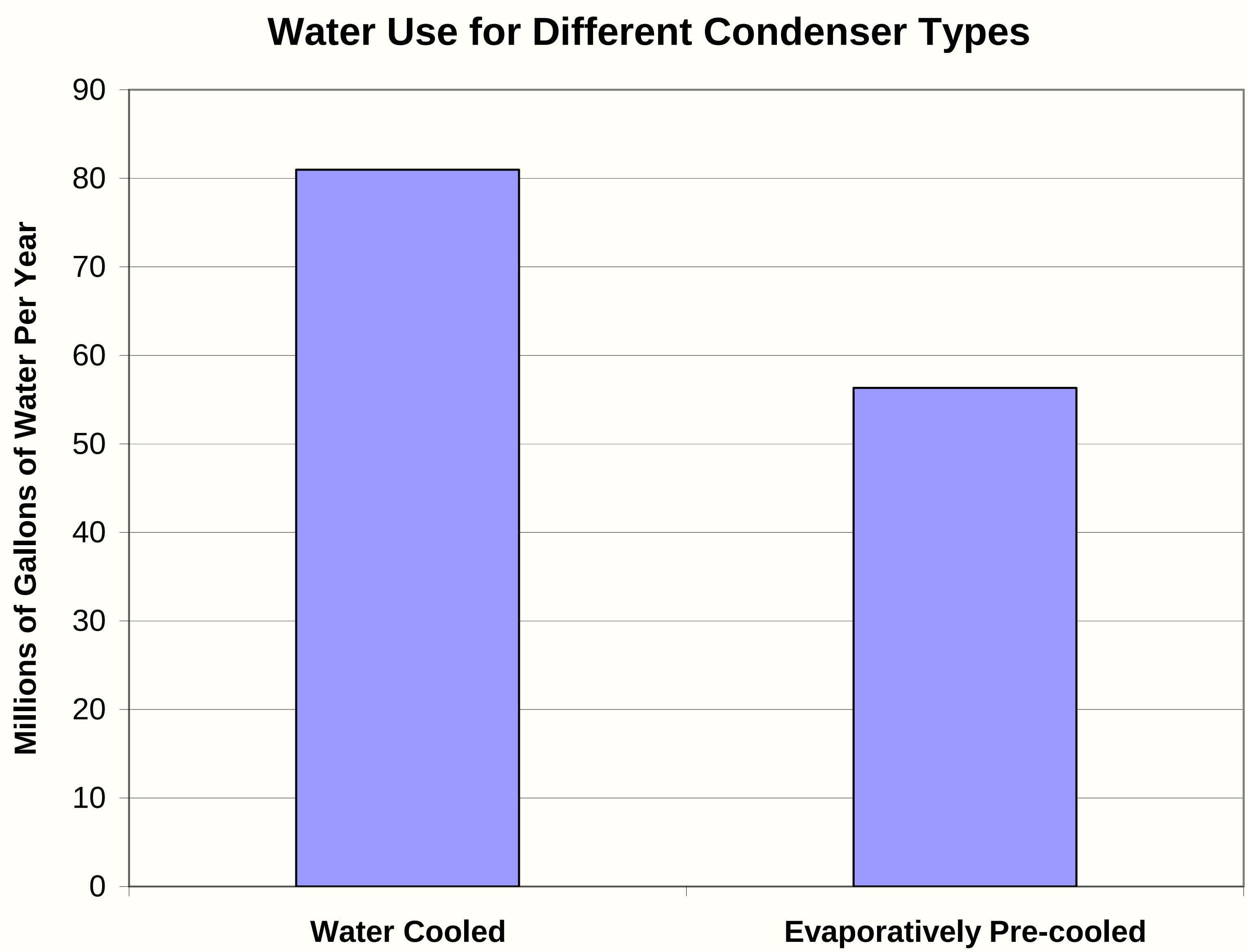
12000
10000
8000
6000
4000
2000
0
Electricity Produced [MWe-hr]
0
1
2
3
4
5
6
7
8
9
10
11
12
13
Month Number
Water Cooled
Evaporatively Pre-cooled
Air Cooled



Effect of Purchase Price of Electricity on Yearly Revenue
(Water Cost = $2/kgal)
Water Cooled
Evaporatively Pre-cooled
Percent Increase in Yearly Revenue
(Compared to Air-Cooled)
6.0%
4.0%
2.0%
0.0%
-2.0%
-4.0%
0.00
0.04
0.08
0.12
0.16
0.20
0.24
Price of Electricity [$/kWh]



Effect of Water Price on Yearly Revenue
(Electricity Price = $0.18/kWh)
Water Cooled
Evaporatively Pre-cooled
Percent Increase in Yearly Revenue
6.0%
5.0%
4.0%
3.0%
2.0%
1.0%
0.0%
0.00
1.00
2.00
3.00
4.00
5.00
6.00
7.00
Price of Water [$/1000 gallons]


Water Use for Different Condenser Types
Millions of Gallons of Water Per Year
90
80
70
60
50
40
30
20
10
0
Water Cooled
Evaporatively Pre-cooled

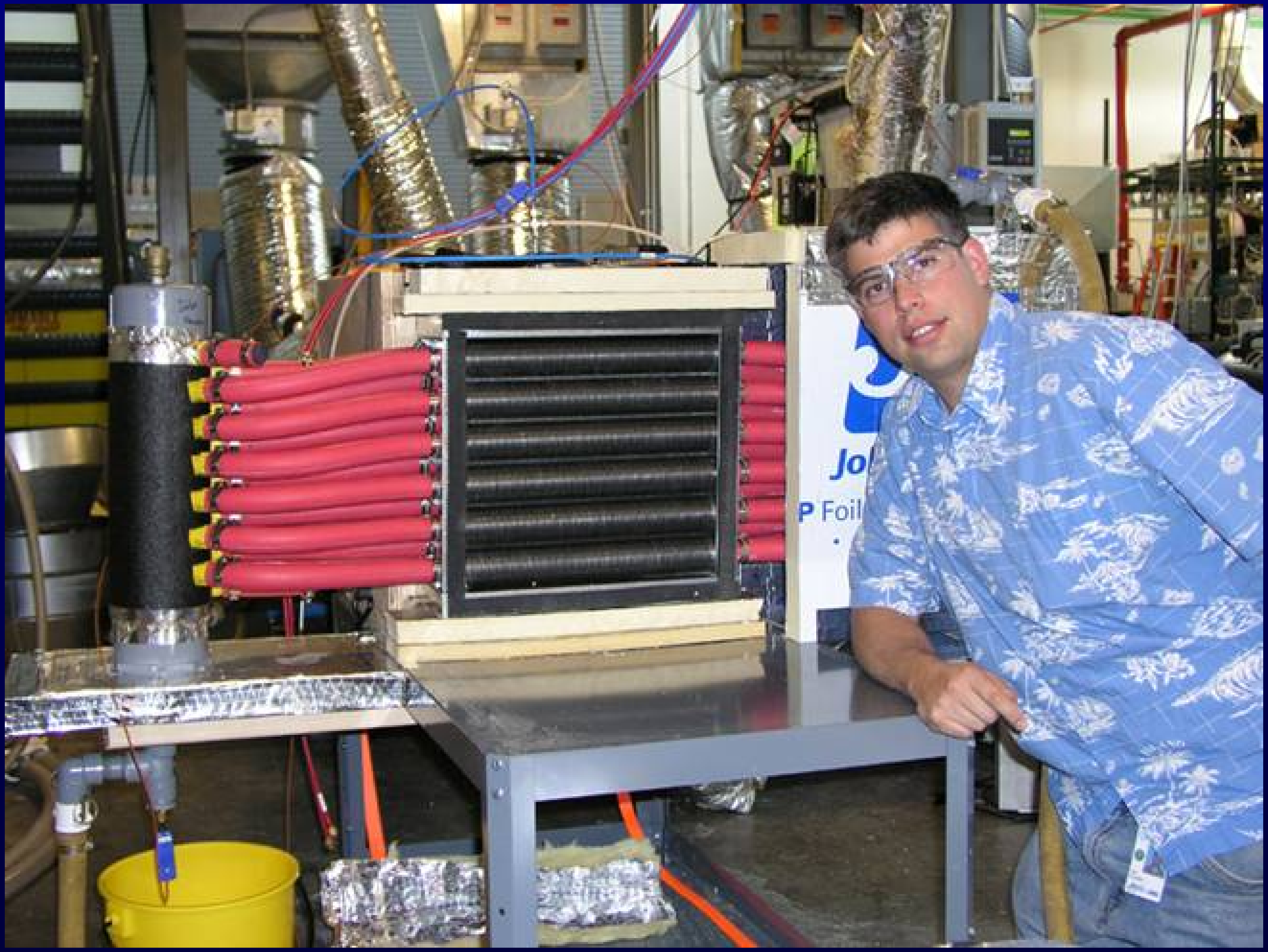
Next Steps

- Evaluate potential for water restrictions
- Develop full plant EES model
- Improve cost estimation
- Analyze parallel wet-dry system

Brief Review of NREL R&D on Advanced Fins for Air-Cooled Condensers

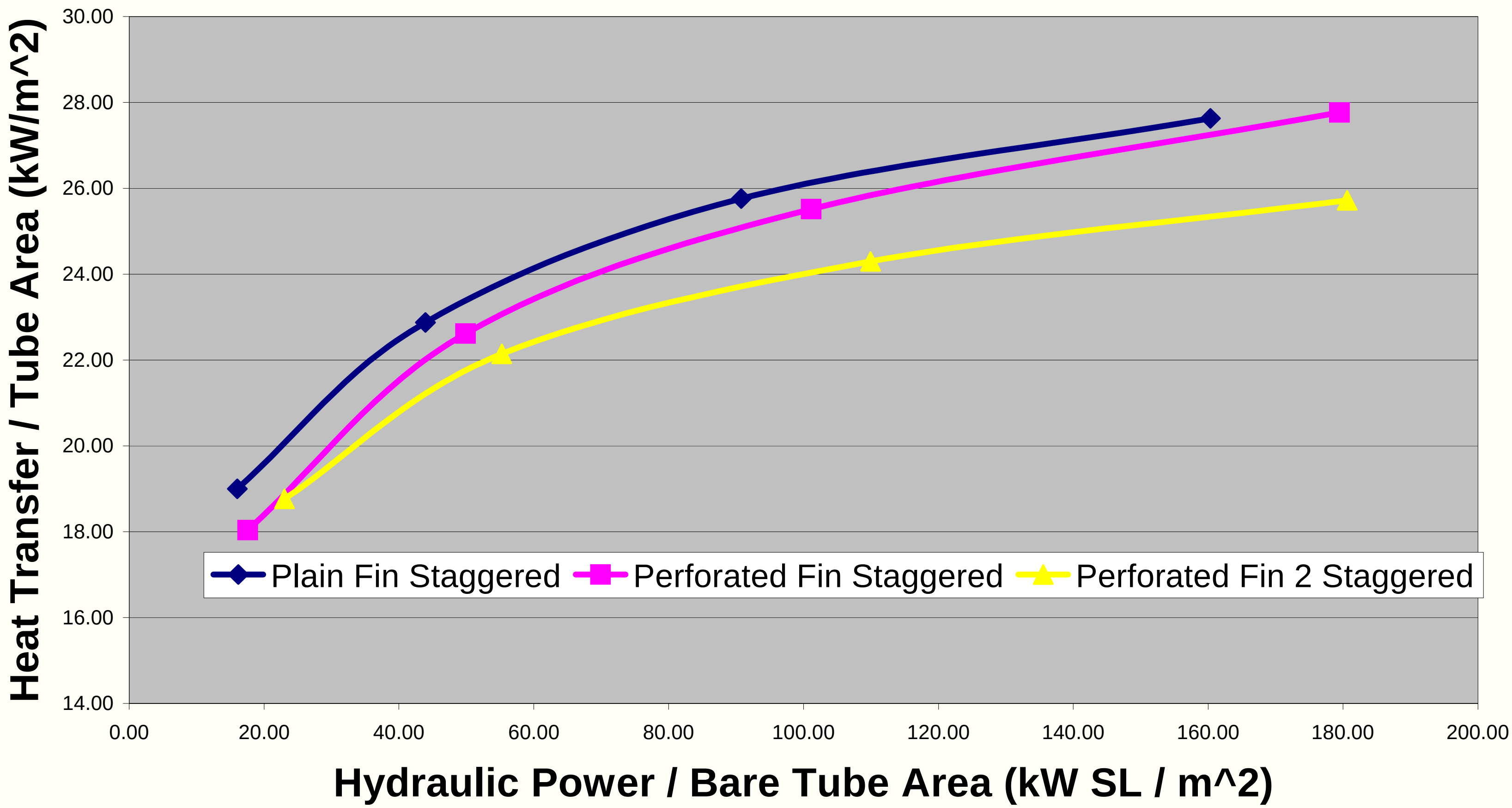
McElroy Enhanced Fins

Test Section

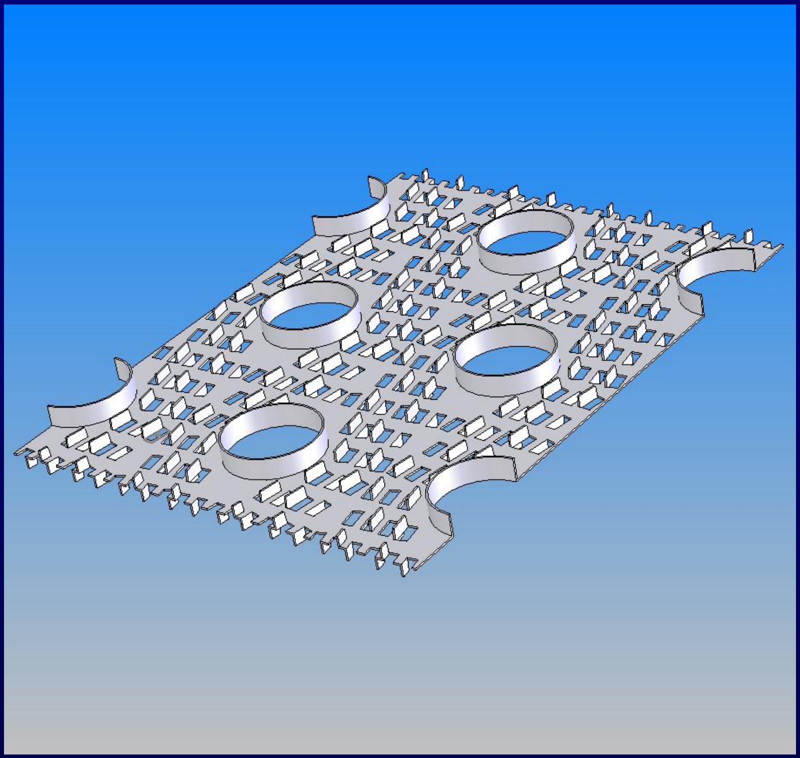


Heat Transfer vs. Hydraulic Power

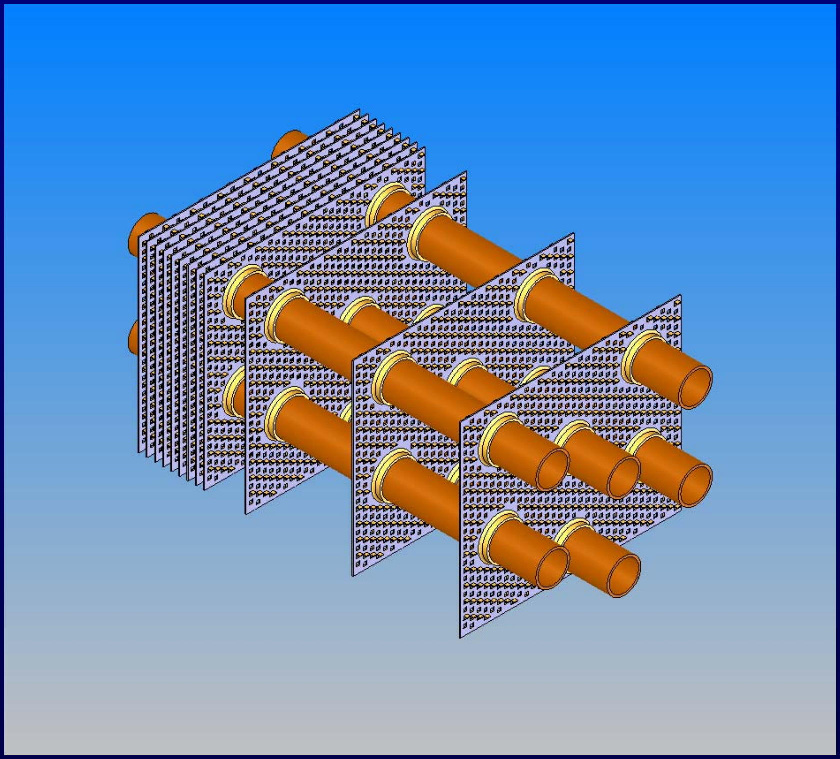
Different Fin Types (Staggered Array)



Tabbed Fin Concept



Tabbed Plate Fin



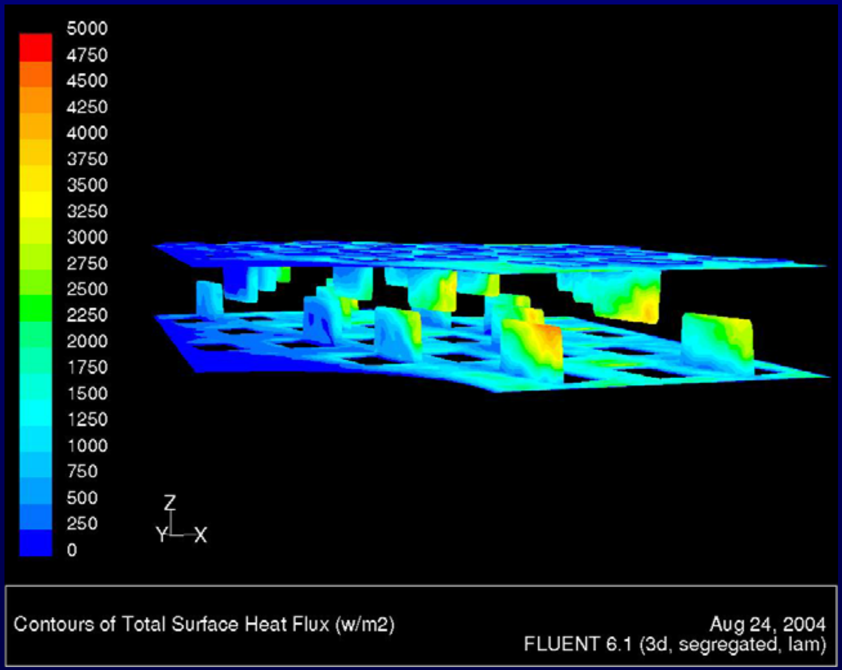
Tabbed Plate Fin Heat Exchanger

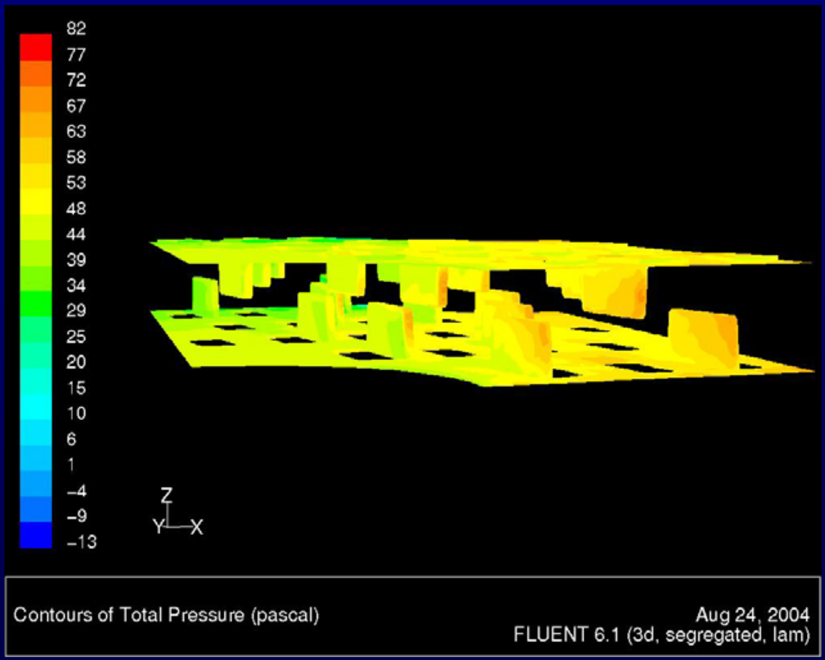
Individual Fins

GEA fins w/spacers

NREL tabbed circular fin

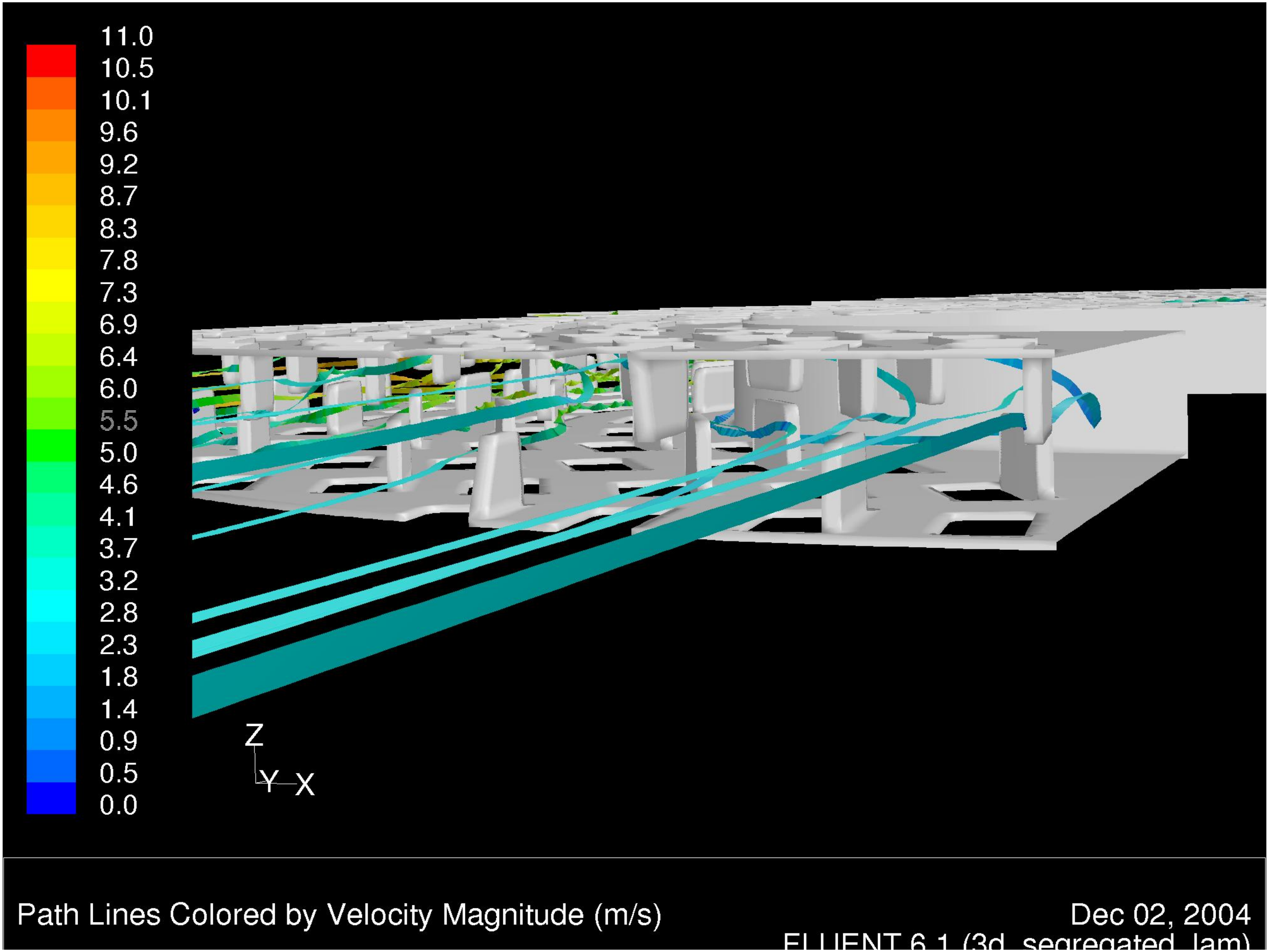
Detailed CFD Model Isometric Views: Heat Flux and Total Pressure





Surface Heat Flux

Total Pressure


11.0
10.5
10.1
9.6
9.2
8.7
8.3
7.8
7.3
6.9
6.4
6.0
5.5
5.0
4.6
4.1
3.7
3.2
2.8
2.3
1.8
1.4
0.9
0.5
0.0
Z
Y
X
Path Lines Colored by Velocity Magnitude (m/s)
Dec 02, 2004
FLUENT 6.1 (3d, segregated, lam)

Recent Tabbed Fin CFD Results